An integrated-circuit based wide range electrometer implemented with automatically ranged linear display

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An electrometer using a complementary metal-oxide semiconductor bilateral switch for automatic range control has been built. This circuit provides linear analog output over six orders of magnitude for current measurement without the need for constant adjustment of offset at different ranges. The application of integrated circuits makes the whole system stable and can be readily constructed.

I. INTRODUCTION

In the measurement of dc current for the range of 10^{-6}–10^{-12} A, a stable electrometer is required. The electrometer circuit is usually implemented by simply probing the voltage drop on a load resistor using a sensitive voltage amplifier.[1] In this scheme, different values of the load resistor are needed to cover multi decade range without saturating the voltage amplifier. This results in different circuit impedances and input biasing to the voltage amplifier. It may consequently cause the offset variation when the load resistor is changed. Another scheme for the galvanometric current measurement is obtained by a current to voltage converter using the nearly ideal character of an operational amplifier.[2] In this case, the input circuit is not changed during the range selection so that the problem of offset variation can be greatly reduced. Although the principle of operation is simple, the commercially available electrometer uses complicated circuitry and high quality contact switches for wide range measurement. It is rather expensive and inconvenient for general purpose current monitoring where the close attachment of the electrometer to the current source is usually needed. In this report, we will describe a novel circuit based on a modified current-voltage (*I-V*) converter which makes possible the usage of complementary metal-oxide semiconductor (CMOS) bilateral switches for range selection. The resultant electrometer is very compact in size and can be easily built.

II. CURRENT TO VOLTAGE CONVERTER

The typical *I-V* converter is shown in Fig. 1 where the inverting configuration is used for the operational amplifier. In Fig. 1(a), the output voltage is given by

$$V_o = -IR_f. \tag{1}$$

Here the feedback resistance, $R_f = R_i + R_{si}$ is defined by selecting the range switch SW_i with R_{si} being the on resistance of SW_i. Because all the R_i's are connected to the inverting input of op-amp, a carefully designed circuit geometry is required to minimize the noise coupling as well as the input stray capacitance which may result in undesired oscillation.[3] Furthermore, since the off resistance of the range switches SW_i must be much larger than the maximum R_f to avoid error due to leakage current, a high quality mechanical switch is inevitable.

Figure 1(b) is a modified circuit. Instead of switching on the feedback resistance, the current range is defined by selecting the feedback factor in the output circuit. The output voltage is given by

$$V_o = -IR_f\left(\frac{R_a+R_b}{R_b}+\frac{R_a}{R_f}\right). \tag{2}$$

Here $R_f = R_1 + R_{si}$ is the feedback resistance and $R_b/(R_a+R_b)$ is the feedback factor. In the case of $R_f \gg (R_a \| R_b)$ and $R_{si} \ll R_1$, Eq. (2) becomes

$$V_o = -IR_1\frac{R_a+R_b}{R_b}. \tag{3}$$

Since only one resistor is connected to the input of the op-amp, the input stray capacitance and the noise pickup can be kept at minimum and the circuit stability will be improved. Another advantage is that the off resistance of the range switches SW_i has little effect on the circuit operation. The general purpose CMOS bilateral switch can be used for further simplifying the system.

III. OVERALL CIRCUIT DESCRIPTION

Figure 2 is the detailed circuit of the electrometer system. As described above, the IC1 functions as a *I-V* converter. Since a JFET input operational amplifier has a very high input impedance ($\approx 10^{12}$ Ω), it requires a very low input bias current ($\approx$50 pA). The 20-kΩ trimming resistor provides the necessary offset nulling. The 10-kΩ resistor and two diodes at the input terminals protect the device from unexpected high current or voltage spike at the input. The 1-MΩ feedback resistor is connected through the six bilateral switches to the voltage divider network at the output terminal. The output voltage V_o is obtained from the voltage follower IC2a which also drives a 1-V full-scale voltmeter. Six current ranges can be selected by switching on the corresponding analog switch. From Eq. (3), the ratio of I/V_o can be successively changed from 10^{-11} to 10^{-6} A/V.

The range switches are driven by the IC4 which is a BCD-to-Decimal decoder. The A, B, C, D inputs of IC4 are connected to IC3 which operates as a binary up/down

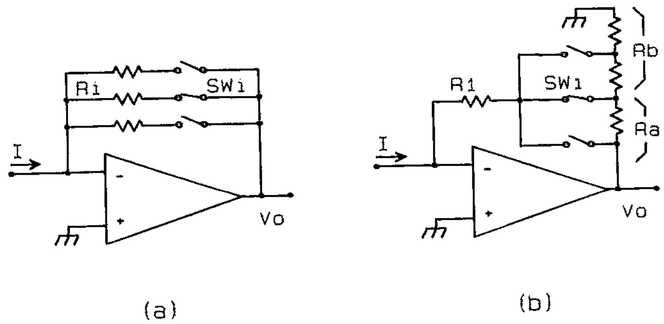

FIG. 1. Two types of current to voltage converter.

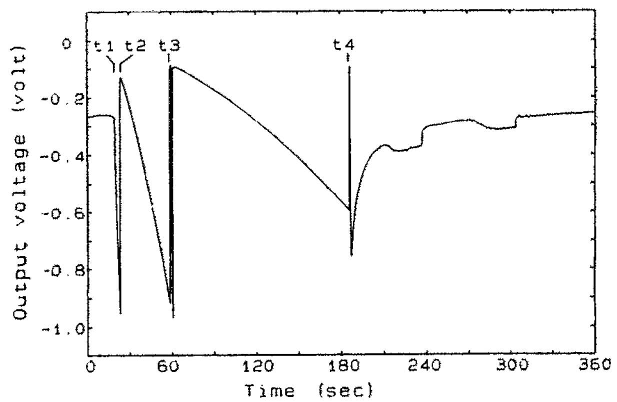

FIG. 3. Measurement of the ion current in the ionization gauge when the pressure is varied.

counter. In this manner, the binary signal of IC3 determines which one of the range switches is being actuated. Meanwhile, six light-emitting diodes (LEDs) are connected to the outputs of IC4 to indicate the range status.

The IC2b, IC2c, and IC2d derive the required pulse to change the binary data in IC3. The IC2b is implemented as a pulse generator with repetition rate of 1 pps. The IC2c and IC2d are voltage comparators which informs the counter, IC3, to increase or decrease its data. When the input voltage V_x of IC2c and IC2d is between -0.95 and -0.095 V, both of their outputs are low and SWa is opened. The data of IC3 will not be changed. When $-0.095\ \text{V} < V_x < 0$ V, IC2c becomes high. In this case, SWa is closed. The IC3 is clocked in the up direction and the electrometer is switched to a more sensitive range. On the contrary, when $V_x < -0.95$, IC2c goes low while IC2d goes high. The IC3 is clocked downward and the I-V converter is switched to the less sensitive range.

The voltage V_x can be controlled in two operation modes determined by SW1. If SW1 is in the manual position, pressing the up and down push buttons initiates the IC3 in the up and down directions, respectively. When the SW1 is positioned to auto, the counter IC3 will be clocked according to the voltage V_o. In this way, for a given input current I, the sensitivity of the electrometer will be automatically switched to the range such that V_o falls between -0.95 and -0.095 V. Finally, the diode and the 10-μF capacitor at the IC3 circuit serves to power-up-reset the counter. The switches SWb and SWc are installed to limit the binary data of IC3 between 0 and 5.

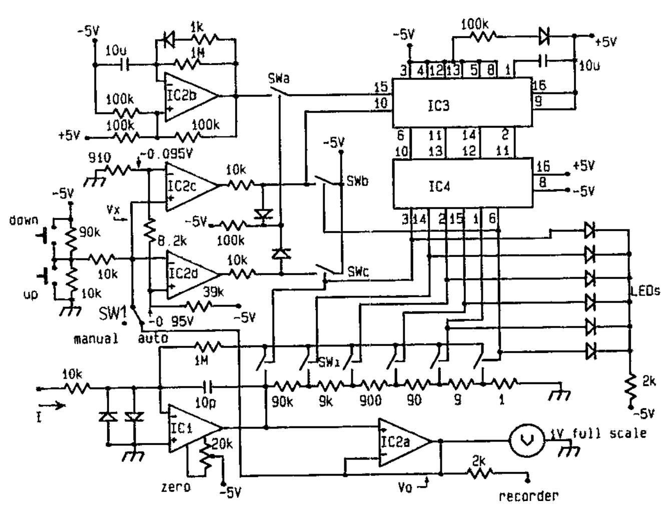

FIG. 2. Circuit detail of the electrometer. IC1, LF351; IC2, LM 324; IC3, CD4029; IC4, CD4028; SWa, SWb, SWc, SWi, CD4066. All the ICs are powered by a ± 5-V regulated power supply.

IV. PERFORMANCE

The electrometer has been tested by feeding some reference currents to the input terminal. It shows high performance with respect to the accuracy and stability. A stable reading with accuracy within 2% is obtained over the 10^{-6}–10^{-10} A/V ranges. Some fluctuation in the reading is observed for the 10^{-11} A/V range which may correspond to an accuracy of 5%. This fluctuation possibly arises from the input noise voltage at LF351. The use of low noise components at the input stage may improve the situation. The offset variation is negligible when the range is switched over six decades.

The performance of automatic ranging has been checked by the measurement of the ion current in a hot-cathode vacuum ionization gauge. When the conventional electrometer in the ionization gauge controller, model IM210 made by Leybold–Heraeus GmbH, is replaced by this circuit, the monitoring of pressure becomes more convenient. Figure 3 shows the typical measurement on a vacuum system with oil diffusion pump. The ion current is continuously monitored when the high vacuum valve is closed at t1 for a period of time and then opened again at t4. Before t1, the ion current is 0.25×10^{-8} A which corresponds to a pressure of 5×10^{-6} mbar. After t1, the ion current increases monotonically and the electrometer automatically switches to the range of 10^{-7}–10^{-6} A/V at t2 and t3, respectively. When the valve is re-opened at the time t4, the electrometer switches quickly to the range of 10^{-8} A/V. The ion current indicates the gradually lowering of pressure with some fluctuations due to the variation of pumping speed which usually occurs in an oil diffusion pump. It is also observed at t3 that the bouncing between adjacent ranges happens at the range boundary. This can be eliminated, if necessary, by making some hysteresis to the comparator circuit of IC2c and IC2d.[3]

V. DISCUSSION

The implementation of CMOS bilateral switches in the modified current to voltage converter greatly simplifies the circuit operation for wide range current measurement. The completed automatically ranged electrometer shows satisfactory performance in stability and accuracy. Its compactness and all-solid-state feature also make it attractive for general purpose experiments.

ACKNOWLEDGMENTS

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[2] *Linear Applications Handbook* (National Semiconductor Co., Santa Clara, CA), Vol. 1.

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